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Effectiveness of crop residuals in ethanol and pyrolysis-based electricity production: A stochastic analysis under uncertain climate impacts

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ABSTRACT

Taiwan aims to replace all nuclear power with renewable energy by 2025, and thus how much electricity from such sources can actually sustain or improve its energy structure must be thoroughly evaluated. This study is designed to explore the Taiwan's bioenergy potential in the face of climate change and climate-induced crop yield change. Multiple bioenergy technologies and energy crops and residuals are embedded in a two-stage stochastic programming with recourse model to discover their efficiency under changes in crop yields and market conditions. The results show that up to 2.26% of total electricity demand can be fulfilled with pyrolysis-based electricity and more than 3.1 million tons of emission reduction can be achieved. Climate-induced crop yield change, if it is small, shall not have considerable influences on bioenergy technology selection and bioenergy output, but land use may be altered considerably with an additional $NT 2.88 billion dollars in government expenditures on support programs.

1. Introduction

Although the share of nuclear power has declined from more than 50% in 1980s to approximately 16% in 2017, nuclear power has still played an important role in Taiwan's energy supply and economic growth. However, based on the latest announcement of Taiwanese government, all nuclear power plants will be shut down in or before 2025 so that Taiwan can be treated as a non-nuclear country afterward. Since the electricity previously generated by nuclear power is planned to be totally replaced by clean and renewable energy, it is crucial to analyze the potential effectiveness of Taiwan's renewable energy development.

Renewable energy is considered to be an effective method to enhance energy security by increasing proportion of domestically produced energy and by replacing import requirements (McCarl and Schneider, 2003). Another benefit associated with renewable energy production is climate change mitigation, which tries to revert the adverse effects such as increased probability of hurricanes, ocean level rise, and dissertation resulted from global climate shift (Guieysse et al., 2013; IPCC, 2007; Marta et al., 2012; McCarl et al., 2007). Because Taiwan is a tiny island is vulnerable to ocean level rise (via salinization of crop land and ground water) and increased occurrences of typhoons (various damages to society and agriculture), development of renewable energy can be of particular interest to Taiwan. Among renewable energy alternatives, bioenergy has been intensively studies because one-third or approximately 280,000 ha (ha) of cropland is released due to higher production and lower competition power in the world commodity markets, providing a substantial amount land for energy crop plantation and bioenergy production.

To analyze how bioenergy benefits Taiwan in terms of energy security and climate change mitigation, a considerable amount of studies have been conducted (Chang, 2002; Chen et al., 2011; Kung et al., 2013; Kung and Zhang, 2015). Although their results suggest that, ceteris paribus, bioenergy could be a potential source to provide electricity and transportation fuel, they obtain this conclusion based on the assumption that climate change will not impact crop yields. However, this assumption should be relaxed because studies have shown that climate change will inevitably and eventually induce changes in crop yield and agricultural activities and because agriculture is the basis of bioenergy production, any potential change occurring in agricultural sector merits more investigation to explore subsequent bioenergy consequences. IPCC's (2007, 2014) reports show that bioenergy analysis

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should take climate-induced impacts into account because changes in temperature and precipitation are major determinants of agricultural productivity. Climate-induced impacts on agricultural productivity and food security (Asseng et al., 2011; Chang, 2002; Chang et al., 2012; Chen et al., 2016; Lobell et al., 2013; Matsui et al., 2000; Mangoyana and Smith, 2011; McCarl, 2006; Reilly et al., 2002b; Porter et al., 2014; Rosenzweig et al., 2002; Sanchez et al., 2014), and on the bioenergy consequences have been conducted widely (Erdogdu, 2008; Fridahl, 2014; Haberl et al., 2011; Karp et al., 2015; Souza et al., 2015), but rare of them discuss how the climate change will influence the bioenergy production, as well as the social economic and environmental effects for regional development or for a specific nation and region.

To discover whether bioenergy can be an effective method to enhance Taiwan's energy security in the face of climate-induced crop yield changes and, to what extent, bioenergy can be a reliable electricity supply, this study accommodates multiple energy feedstocks such as sweet potato, willow, poplar, switchgrass, rice straw and energy crop residuals, and bioenergy technologies such as ethanol, co-firing, and pyrolysis into a two-stage stochastic programming with recourse model (SPR) to examine the effectiveness of Taiwan's bioenergy production and subsequent agro- and socio-economic consequences under various climate-induced crop yield changes. Specifically, the study investigates following issues subject to climate impacts: (1) ethanol and electricity production under various market conditions; (2) government expenses on bioenergy and social welfare consequences; (3) potential land-use change and resource allocation; and (4) pyrolysis by-product (biochar) utilization and emission offset capacity.

By accomplishing these tasks, this manuscript has made several contributions. Since previous Taiwanese bioenergy studies are (a) primarily based on deterministic models, which did not take climate impacts into account, or (b) to examine crop yield change under climate change with econometric analysis, which did not tell the net shift among agricultural activities and resource allocation, our first contribution is to firstly integrate the agricultural activities, bioenergy production, and climate impacts into a single study. We provide useful information to Taiwanese government so that decision-makers may be able to formulate a more appropriate future energy plan (or redesign existing ones). Second, crop residuals are jointly utilized in this study to provide information of potential treatment of agricultural wastes. Since climate-induced yield change may alter the current agricultural practice and the availability of feedstocks may be fluctuated, the second contribution of this study provides a hint about bioenergy potential from the utilization of crop residuals under climate change. The third contribution made by this study is that the interrelationship between bioenergy production and agricultural activities under crop yield changes is fully illustrated. The results can provide clues for changes in land fertility and bioenergy production parameters in the dynamic framework, which consequently can be helpful in bioenergy studies. The fourth and last contribution of this study is that our results compare the influences of climate change and market operations, which may be useful for future agricultural and energy policies. For example, we show that bioenergy production may remain at a stable level while the agricultural practice could alter considerably in the face of climate change. This implies that, even climate change may shift the agricultural activities among regions, the development of bioenergy and its effectiveness can be assured.

2. Literature review

To mitigate climate change and reduce the occurrences of extreme events, there is a consensus to switch to low-carbon fuels to assure sustainable development (Fargione et al., 2008; Searchinger et al., 2017). Bioenergy is considered as an effective approach to improve energy sustainability and has been intensively studied (Haberl et al., 2011; Luo et al., 2017; Nie et al., 2017; Scarlat and Dallemand, 2011; Tan et al., 2018; Tsatsaronis, 2017), especially in countries with substantial amount of cropland and forests (Bergtold et al., 2017; Campiche et al., 2010; Cutz et al., 2017; Jeffers et al., 2013; Mei and Wetzstein, 2017; Hagos et al., 2017; Karp et al., 2015; McCarl and Schneider, 2000; Winchester and Reilly, 2015; Ziska et al., 2009). However, in terms of climate change mitigation, whether bioenergy is actually a low-carbon fuel still under debates (Fargione et al., 2008; Searchinger et al., 2008; Wang, 2007). For example, Field and Campbell (2008), Searchinger et al. (2008), Winchester and Ledvina (2017), and Wise et al. (2015) all agree that bioenergy can be potentially useful in combating climate change, but the feedstock selection and process involved in bioenergy production must be carefully examined to assure it does not emit additional greenhouse gases.

Another concern regarding bioenergy production is food-to-energy competition. To reduce fluctuation of commodity prices and maintain the quantity traded in international markets so that the poorer countries will not be greatly suffered by bioenergy production, Arvizu (2008), Campiche et al. (2010), and Fewell et al. (2016) thus propose the use of cellulosic bioenergy technology in which crop residuals become the primary feedstock in bioenergy production. With this innovation of technology, bioenergy is now considered to be a good choice to enhance energy security and combat climate change, but a crucial issue to understand how its production can be altered from the sector it relies is generally ignored.

The effectiveness and efficiency of bioenergy production is highly dependent on agricultural practice which can be greatly influenced by the climate conditions. As studies show that changes in temperature and precipitations has already resulted in shifts in agriculture, (Asseng et al., 2011; Chang, 2002; Chang et al., 2012; Chen et al., 2016; Darwin et al., 1995; Kaiser et al., 1993; McCarl, 2006; Reilly et al., 2002b) and crop yield response under different climate pattern will alter (Chen et al., 2016; Iizumi et al., 2013; Liu et al., 2014; Lobell and Burke, 2010; Lobell et al., 2012; Shuai et al., 2013a, 2013b), it becomes an urgent issue to analyze how such climate-induced impacts will alter the current agricultural activities and subsequent bioenergy production. Since bioenergy is usually studied with historical crop yields (Chen et al., 2011; Kung et al., 2014; Schaffer and Bernauer, 2014; Tewfik et al., 2011) that bring in less realistic, or even less reliable conclusions about economic and environmental effects, changes in crop yield due to global climate shift should be integrated into bioenergy analysis to reflect reality.

Based on Taiwan's 2017 announcement about its energy plan, all nuclear power plants that provide approximately 16% of Taiwan's electricity (or 32 billion kWh) will be phased out before year 2025, leaving less than 7 years for Taiwan to recover such a great electricity shortage. Once the electricity demand cannot be fulfilled, it will be extremely hazardous to Taiwan's economic development. Hence it is obvious that an immediate increase in renewable energy production becomes a prior pursuit to Taiwan. Under such a consideration, exploring how Taiwan's bioenergy production will be altered under various climate impacts should be taken into account to provide a more robust result that can be referred for Taiwanese decision-making.

After a policy or a program is launched, welfare measures are generally used to evaluate its overall efficiency. A sectoral model that includes price endogeneity, producers' and consumers' responses to market price signals, international trade activities, and potential policy interventions is considered to be an useful approach (Chang et al., 2012; Chen et al., 2011; Kung and Zhang, 2015; McCarl, 2006). Climate-induced impacts can also ben integrated in to such modeling formulation because impacts of crop yield change on the volume of international trade and the size of international adjustments are usually assumed insignificant (McCarl, 2006; Reilly, 1995), all factors in non-agricultural sectors will be assumed constant in this study. Therefore, this study adopts such a framework to incorporate climate-induced influences on crop yields to provide a more robust and informative analysis.

3. Methodology

To investigate the social economic effects from bioenergy production, the analytical framework must incorporate entire agricultural sector so that the agricultural responses can be fully depicted. Samuelson (1952) illustrates a mathematical programming approach by showing that the market equilibrium of a competitive market can be obtained by maximizing the net consumer and producer surplus. This structure is then evaluated by McCarl and Spreen (1980), and a number of subsequent studies (Adams et al., 1990, 1992; Chen et al., 2011; Chang et al., 2012; Kung et al., 2013; McCarl, 2006). McCarl and Spreen (1980) demonstrate that this framework can well portray an economic system in a perfect competitive market, and thus it is useful in policy analysis. Thereafter this analytical structure has been rigorous employed in many agricultural, resource, and environmental studies including soil protection (Chang et al., 1992), acid rain (Adams et al., 1992), renewable energy (Tyner, 1979; Chen et al., 2011), climate change (Adams et al., 1999; McCarl, 2007; Reilly et al., 2002a), ozone (Hamilton et al., 1985), GHG mitigation (Adams et al., 1995; Kung and Zhang, 2015; McCarl and Schneider, 2000,), policy evaluation (Chang et al., 1992; Chen et al., 2011; Coble et al., 1992), and pyrolysis applications (Kung et al., 2014;).

3.1. Background of Taiwan Agricultural Sector Model

The Taiwan Agricultural Sector Model (TASM) is developed by Chen and Chang (2005) to examine the policy impacts such as changes in production practice and land use., and several subsequent studies utilize this framework to analyze the economic and environmental issues related to agriculture (Chang et al., 2012; Chen et al., 2011; Kung et al., 2013). Since this modeling framework assumes perfect competition, individual consumers and producers are assumed to be price-takers. Additionally, all counties in Taiwan are incorporated and separated into 4 major production and processing regions where crop production and livestock mix activities are specified at the sub-regional level, and input markets such as irrigation, labor, and fertilizer are specified at regional level. This agricultural sector model accommodates more than 87% of total agricultural product value of Taiwan.

3.2. Formulation of stochastic agricultural sector model

Since bioenergy production requires a substantial amount of agricultural commodity, and crop yields are subject to change under climate-induced impacts such as a shift in precipitation and changes in regional temperature, we need to reformulate the deterministic agricultural sector model to a stochastic version. The concept where the stochastic property gets involved is explicitly explained here. Thus the model should contain multiple states of nature to reflect that the variability of crop yields. The farmers will make planting decision in the first stage before actual information is revealed in the harvesting period (i.e., whether, crop yield, commodity prices), and the decisions made in the first stage cannot be altered in the later stage. In the meanwhile, we also need to specify the supply-demand balance constraints to ensure market clearance at each state of nature in the second stage. Under such a consideration, we can extend the deterministic model to a stochastic programming with recourse model (SPR), which is illustrated in Lambert et al. (1995), Chen and McCarl (2000), and Chang et al. (2012). The stochastic model is algebraically expressed as follows:

$$\begin{aligned} MaxW \;=\; & \sum_s \rho(s)^*\{\sum_i \int \psi(Q_{is})dQ_{is} - \sum_k \int \alpha_k(L_k)dL_k \\ & - \sum_k \int \beta_k(R_k)dR_k \\ & - \sum_i \sum_k C_{ik}X_{ik} + \sum_i \int ED(Q_{is}^M)dQ_{is}^M \\ & + \sum_i \int EXED(TRQ_{is})dTRQ_{is} \\ & - \sum_i \int ES(Q_i^X)dQ_i^X + \sum_i [tax_i{}^*Q_{is}^M + outtax_i{}^*TRQ_{is}]\} \\ & + \sum_i P_i^G{}^*Q_i^G + \sum_k P^L{}^*AL_k + \sum_j SUB_j{}^*AL_j \\ & - P_{GHG}{}^* \sum_g GWP_g{}^*GHG_g \end{aligned} \tag{1}$$

Subject to

$$Q_{is} + Q_{is}^X + Q_i^G - \sum_k Y_{iks}{}^*(1+CCYIELD_i)^*X_{ik} - (Q_{is}^M + TRQ_{is}) \le 0 \quad \forall i, s \tag{2}$$

$$\sum_i X_{ik} + AL_k - L_k \le 0 \quad \forall k \tag{3}$$

$$\sum_i f_{ik}X_{ik} - R_k \le 0 \quad \forall k \tag{4}$$

$$\sum_{i,k} E_{gik}X_{ik} - GHG_g \le \quad 0 \quad \forall g \tag{5}$$

where

s	State of nature s
Q_i	Domestic demand of i^{th} product
Q_i^G	Government purchases quantity for price supported i^{th} product
Q_i^M	Import quantity of i^{th} product
Q_i^X	Export quantity of i^{th} product
$\omega(Q_i)$	Inverse demand function of i^{th} product
P_i^G	Government purchase price on i^{th} product
C_{ik}	Purchased input cost in k^{th} region for producing i^{th} product
X_{ik}	Land used fori^{th} commodities in k^{th} region
L_k	Land supply in k^{th} region
$\alpha_k(L_k)$	Land inverse supply in k^{th} region
R_k	Labor supply in k^{th} region
$\beta_k(R_k)$	Labor inverse supply in k^{th} region
P^L	Set-aside subsidy
AL_k	Set-aside acreage in k^{th} region
$ED(Q_i^M)$	Inverse excess import demand curve for i^{th} product
$ES(Q_i^X)$	Inverse excess export supply curve for i^{th} product
TRQ_i	Import quantity exceeding the quota for i^{th} product
$EXED(TRQ_i)$	Inverse excess demand curve of i^{th} product that the import quantity is exceeding quota.
tax_i	Import tariff for i^{th} product
$outtax_i$	Out-of-quota tariff for i^{th} product
Y_{ik}	Per hectare (ha) yield of i^{th} commodity produced in k^{th} region
f_{ik} Y_{ik}	Labor required per hectare of commodity i in region k
f_{ik}	Labor required per hectare of commodity i in region k
SUB_j	Subsidy on planting j^{th} energycrop
EC_{jk}	Planted acreage of j^{th} energy crop in k^{th} region
P_{GHG}	Price of GHG gas
GWP_g	Global warming potential of g^{th} greenhouse gas
GHG_g	Net greenhouse gas emissions of $g^{th}gas$
E_{gik}	g^{th} greenhouse gas emission from i^{th} product in k^{th} region

As illustrated in the objective function (i.e., Eq. (1)), the demand and supply components included in the parenthesis {•} must reflect the state of nature and are controlled by the factor of $\sum_s \rho(s)$. Other

components such as crop subsidy that are not dependent on the state of nature are added after the {•}. This objective function maximizes the social welfare by maximizing the consumer surplus and producer surplus from consuming and producing agricultural commodities and bioenergy. The international trade activities and the domestic policies such as aside program and carbon trade are also specified. Eq. (2) is to balance the supply and demand by ensuring the quantity sold plus export should not exceed the quantity produced plus import, and the notation CCYIELD reflects the potential yield change under climate impacts. Eq. (3) balances the land use so that all hectares employed by all agricultural activities must be equal to or less than total land available. Eq. (4) is another resource constraint which is similar to Eq. (3) by ensuring labor engaged in agricultural practice should not exceed total labor supply. Eq. (5) is another balance constraint that indicates the total emissions of each kind of greenhouse gases from agricultural activities should not exceed their total emission.

To verify whether the model can accurately portray Taiwan's agricultural sector and is useful in this study, we have validated it by comparing the model results and actual data (i.e., commodity productions, land-use patterns), and the results show that the deviations between simulation results and actual data are highly coincided, implying the model used in this study should be valid. The result of validation has been provided in Table 1, which is shown as below:

3.3. Data source

The data used in this study originates from various sources including government statistics and research reports. Specifically, data is obtained from Taiwan Agricultural Yearbook, Taiwan Agricultural Prices and Costs Monthly, Trade Statistics of the Inspectorate-General of Customs, Taiwan Area Agricultural Products Wholesale Market Yearbook, Production Cost and Income of Farm Products Statistics, Forestry Statistics of Taiwan, and Commodity Price Statistics Monthly. The data sets have been updated to 2013 (i.e., data of crop output, labor availability, input use, cropland availability, etc.) so that the knowledge about the shift of resource allocation and change in land use under yield change and climate impacts may be assessed with latest information. In addition, data set such as elasticity and types of commodities are collected in 2010. They, in general, should not affect the results significantly because elasticities and crop types are relatively stable since then. Parameters associated with bioenergy production and GHG offset come from our previous studies (Kung et al., 2013, 2015). Aside program is based on the expectation of the undersecretary of Agriculture of Taiwan (Prof. Chi-Chung Chen). Price and demand elasticities are primarily obtained from literatures and personal communications.

3.4. Study setup

This study aims to analyze how climate change may alter Taiwan's bioenergy development via changes in crop yields and agricultural practice. We accommodates Chang et al.'s (2012) estimates of Taiwan's yield change and the climate change projections (HADCM) from IPCC as parameters to depict the climate-induced influences on agriculture. Two HADCM projections are selected where projection A models a small change of crop yield while projection B models a moderate yield change. Several energy crops such as sweet potato, willow, poplar, and switchgrass, and their residuals are also specified as potential feedstocks. In addition, since rice is the major commodity that planted on more than 30% of cropland in Taiwan, the utilization of rice straw is also considered. Before the simulation is conducted, it is also necessary to point out that, besides rice straw, the utilization of certain crop residuals occurs only if such crop is planted as energy crop. For example, if willow is not planted, then none of its residuals will be available and subsequently used in bioenergy production. Therefore, which crop residual will be available depends on the simulation results, which cannot be specified at this stage.

Moreover, we assume that all energy crops and their residuals can be used to generate electricity while only energy crops will be used to produce ethanol. Co-firing and pyrolysis are the primary technologies in which the former is to heat biomass with coal while the latter is to heat biomass in the absence of oxygen (pyrolysis reactor). The primary outputs from pyrolysis such as biooil, biogas will be used in electricity generation while biochar will be as a soil amendment to obtain additional agro-economic benefits. Because the output yields and subsequent electricity potential may change considerably under different pyrolysis process, we will adopt two types (fast and slow) of pyrolysis to examine their effectiveness and efficiency.

Market influences will be simulated. To examine how economic factors such as prices of gasoline, electricity, and GHG could affect bioenergy production and associated economic and environmental benefits, different sets of these prices will be examined, where the range of gasoline and coal prices is based on Taiwan's historical trading prices while the value of emission reduction is taken from the Chicago Climate Exchange. Moreover, since 3 popular bioenergy technologies such as ethanol, co-firing, and pyrolysis are integrated, the results will be able to tell which technique (or combination) will be dominant under various market conditions.

To examine the potential land-use change and resource reallocation, all counties in Taiwan are grouped to north (Taipei, Taoyuan, Hsinchu, Miaoli), central (Taichung, Nantu, Changhua, Chiayi), south (Yunlin, Tainan, Kaohsiung, Pingtung), and east (Ilan, Hualian, Taitung) so that the information about which region is most suitable for bioenergy production and most vulnerable to climate change can be explicitly presented to decision-makers.

Table 1
Model Validation for Major Products Based on 2013 Statistics.

Products	Production (ton)		Price (NT$/kg)	
	Observation	Deviation	Observation	Deviation
Rice	1333,018	0.32%	28.61	3.46%
Hog	864,792	−0.19%	86.91	−1.13%
Broiler Chicken	304,354	3.87%	58.17	1.47%
Native Chicken	266,161	1.36%	89.56	0.64%
	Planted area (hectares)			
	Observation	Deviation		
	Rice	268,150	−1.97%	
Set-Aside	262,330	0.89%		

4. Results

Table 2 presents the bioenergy production in the face of crop yield change under various gasoline prices. The results show that sweet potato will be regularly produced as energy crop and thus only sweet potato, its by-products, and rice straw will be considered as feasible bioenergy feedstocks. When the risk of changes in crop yield is small, the net production of both ethanol and electricity is less sensitive to such changes. The results also point out that co-firing is an economically inefficient approach. Electricity is generally generated from pyrolysis that yields higher output and offset capacity. Therefore, the most efficient way to generate electricity in Taiwan is to adopt pyrolysis while the detailed process of pyrolysis depends on Taiwan's objective. Additionally, it is noteworthy to point out that when GHG price increases, ethanol will also be phased out since pyrolysis captures more economic benefits. Under this circumstance, the net electricity generated can be up to 4.537 billion kWh or approximately 2.26% of Taiwan's total electricity demand.

One interesting finding is that crop residuals can be considered as important resources in electricity generation. Rice straw, along with sweet potato vine can provide up to 40.09% of electricity produced when gasoline price is high. This occurs due to that more sweet potatoes will be used to produce ethanol at higher gasoline prices, thereby

Table 2
Energy production under various gasoline prices.

Gasoline Price	NT$/liter	$20	$25	$30	$35	$40
Risk of yield change: Low						
(Scenario A)						
Ethanol Production	1000 l	68,226.94	132,600.00	132,600.00	170,987.24	170,956.95
Electricity Production	1000 kW h	3522,472	2863,573	2900,688	2669,871	2666,250
Electricity@ SWP	%	70.90%	64.12%	64.54%	61.45%	61.42%
Electricity@ SWPvine	%	21.18%	26.14%	25.84%	28.09%	28.11%
Electricity@ Residual	%	7.92%	9.74%	9.62%	10.45%	10.47%
Scenario B						
Ethanol Production	1000 l	68,226.94	132,600.00	132,600.00	170,987.24	170,956.95
Electricity Production	1000 kW h	3522,472	2863,573	2900,688	2669,871	2666,250
Electricity@ SWP	%	70.90%	64.12%	64.54%	61.45%	61.42%
Electricity@ SWPvine	%	21.18%	26.14%	25.84%	28.09%	28.11%
Electricity@ Residual	%	7.92%	9.74%	9.62%	10.45%	10.47%
Risk on yield change: Moderate						
Scenario A						
Ethanol Production	1000 l	60,178.14	130,000.00	130,000.00	130,000.00	156,000.00
Electricity Production	1000 kW h	3793,482	3087,963	3088,988	3090,869	2826,544
Electricity@ SWP	%	72.82%	66.65%	66.65%	66.66%	63.56%
Electricity@ SWPvine	%	19.82%	24.32%	24.32%	24.31%	26.57%
Electricity@ Residual	%	7.36%	9.04%	9.03%	9.03%	9.87%
Scenario B						
Ethanol Production	1000 l	59,957.71	130,000.00	130,000.00	130,000.00	156,000.00
Electricity Production	1000 kW h	3793,107	3091,995	3084,339	3086,370	2824,132
Electricity@ SWP	%	72.83%	66.67%	66.62%	66.63%	63.54%
Electricity@ SWPvine	%	19.81%	24.31%	24.34%	24.33%	26.58%
Electricity@ Residual	%	7.36%	9.02%	9.05%	9.04%	9.88%
Risk on yield change: High						
Scenario A						
Ethanol Production	1000 l	64,703.95	132,600.00	132,600.00	171,270.34	171,269.91
Electricity Production	1000 kW h	3521,410	2863,573	2863,573	2629,167	2629,125
Electricity@ SWP	%	70.92%	64.12%	64.12%	60.92%	60.92%
Electricity@ SWPvine	%	21.16%	26.14%	26.14%	28.46%	28.46%
Electricity@ Residual	%	7.92%	9.74%	9.74%	10.61%	10.61%
Scenario B						
Ethanol Production	1000 l	64,605.48	132,600.00	132,600.00	171,259.63	171,259.63
Electricity Production	1000 kW h	3521,222	2862,292	2862,186	2627,922	2627,922
Electricity@ SWP	%	70.92%	64.11%	64.11%	60.91%	60.91%
Electricity@ SWPvine	%	21.15%	26.14%	26.14%	28.47%	28.47%
Electricity@ Residual	%	7.92%	9.75%	9.75%	10.62%	10.62%

*Electricity price and GHG price are fixed at $1.8/kWh and $5/ton, respectively.

reducing the portion of feedstocks available for pyrolysis. When gasoline price declines to NT$20 or NT$25 per liter, more feedstocks will be used in electricity generation and the contribution of electricity supply from crop residuals declines from 35.88% to 29.1%.

Another important finding is that, at best, only 57.3% of demand of E3-gasolinegas will be satisfied, implying that when pyrolysis is jointly applied with ethanol technology, production of liquid fuel is less desirable in the face of high electricity and GHG prices. So far the results have explicitly indicated that the change in crop yields does not influence ethanol and electricity production considerably, and the amount of the bioenergy produced are primarily affected by the gasoline, electricity, and GHG prices, in which the GHG price has the largest impact and the gasoline price has the smallest one. It is clear that the invisible hand introduced by Adam Smith plays an important role here: bioenergy producers choose to maximize profits by maximizing production of bioenergy that will result in the highest economic profits. More feedstocks are thus transferred to pyrolysis, especially in the form of fast pyrolysis to increase producer surplus.

As indicated in Table 3, Taiwan can achieve a desired level of GHG offset from bioenergy development. Approximately 2.39–3.13 million tons of CO_2 emissions can be reduced, depending on the levels of energy prices. It is noteworthy to show that most of the emission reduction comes from the pyrolysis technology, especially from the slow pyrolysis at high GHG prices. This is explained by that slow pyrolysis yields more biochar and sequesters more carbon, thereby encouraging the adaptation of slow pyrolysis at high GHG prices. On the contrary, a higher electricity price encourages fast pyrolysis that generates more electricity, regardless of the risks on crop yield change. In general, about 1.02–1.39% of Taiwan's total emission can be offset, in which less than 1% of total emission reduction is from the use of ethanol. Although the trivial contribution of emission reduction from ethanol has been evidenced by many studies, it is seldom to see such a small ratio in a large-scale analysis, implying that ethanol may be useful in providing transportation fuel, but may not be a prominent technology in combating climate change.

The crop residuals contribute 43.61–54.43% of total emission reduction, depending on the extent of climate impacts and the market condition. The results indicate that the net emission reduction is much larger than previous studies because of the join application of residuals accompanied with the energy crops. It is worthy to stress that although the use of crop residuals does have positive effects on energy production and emission reduction, removal of such residuals from cropland may result in some environmental and economic side-effects such as potential erosion and more fertilizer application may require further investigation.

Table 4 shows how crop residuals contribute under various gasoline, electricity, and GHG prices. At higher GHG and electricity prices (or such expectations), more farmers will participate with the promotion program, resulting in more supply of crop residuals. Therefore, it is clear that when prices increase, sweet potato vine can play an even more important role in electricity generation and emission offset.

In most cases, utilization of rice straw generates 6.15–10.61% of total electricity, which is smaller than that of sweet potato vines. However, since rice is the major source of carbohydrate in Taiwan, rice

Table 3
Environment consequences from bioenergy production.

Gasoline Price	NT$/liter	$20	$25	$30	$35	$40
Risk of yield change: **Low**						
Scenario A						
Emission Reduction@ Eth	ton	7641	14,851	14,851	19,151	19,147
Emission Reduction@ Elec	ton	2967,597	2528,170	2553,709	2399,552	2396,794
Total Reduction	ton	2975,238	2543,021	2568,560	2418,702	2415,941
%contribution @Ethanol	% of total	0.26%	0.58%	0.58%	0.79%	0.79%
% contribution @SWP	% of total	56.11%	48.26%	48.71%	45.33%	45.30%
% contribution @SWPvine	% of total	31.75%	37.27%	36.95%	39.27%	39.28%
% contribution @Ricestraw	% of total	11.87%	13.89%	13.76%	14.61%	14.62%
Scenario B						
Emission Reduction@ Eth	ton	7641	14,851	14,851	19,151	19,147
Emission Reduction@ Elec	ton	2967,597	2528,170	2553,709	2399,552	2396,794
Total Reduction	ton	2975,238	2543,021	2568,560	2418,702	2415,941
%contribution @Ethanol	% of total	0.26%	0.58%	0.58%	0.79%	0.79%
% contribution @SWP	% of total	56.11%	48.26%	48.71%	45.33%	45.30%
% contribution @SWPvine	% of total	31.75%	37.27%	36.95%	39.27%	39.28%
% contribution @Ricestraw	% of total	11.87%	13.89%	13.76%	14.61%	14.62%
Risk of yield change: **Moderate**						
Scenario A						
Emission Reduction@ Eth	ton	6740	14,560	14,560	14,560	17,472
Emission Reduction@ Elec	ton	3124,246	2660,913	2661,778	2663,169	2488,756
Total Reduction	ton	3130,986	2675,473	2676,338	2677,729	2506,228
%contribution @Ethanol	% of total	0.22%	0.54%	0.54%	0.54%	0.70%
% contribution @SWP	% of total	58.09%	50.71%	50.71%	50.73%	47.27%
% contribution @SWPvine	% of total	30.41%	35.54%	35.54%	35.54%	37.94%
% contribution @Ricestraw	% of total	11.28%	13.21%	13.20%	13.19%	14.10%
Scenario B						
Emission Reduction@ Eth	ton	6715	14,560	14,560	14,560	17,472
Emission Reduction@ Elec	ton	3123,771	2663,949	2658,298	2659,825	2487,053
Total Reduction	ton	3130,487	2678,509	2672,858	2674,385	2504,525
%contribution @Ethanol	% of total	0.21%	0.54%	0.54%	0.54%	0.70%
% contribution @SWP	% of total	58.10%	50.74%	50.68%	50.69%	47.24%
% contribution @SWPvine	% of total	30.40%	35.53%	35.56%	35.55%	37.95%
% contribution @Ricestraw	% of total	11.29%	13.19%	13.22%	13.21%	14.11%
Risk of yield change: **High**						
Scenario A						
Emission Reduction@ Eth	ton	7247	14,851	14,851	19,182	19,182
Emission Reduction@ Elec	ton	2966,252	2528,170	2528,170	2371,276	2371,248
Total Reduction	ton	2973,499	2543,021	2543,021	2390,458	2390,430
%contribution @Ethanol	% of total	0.24%	0.58%	0.58%	0.80%	0.80%
% contribution @SWP	% of total	56.15%	48.26%	48.26%	44.78%	44.78%
% contribution @SWPvine	% of total	31.73%	37.27%	37.27%	39.64%	39.64%
% contribution @Ricestraw	% of total	11.88%	13.89%	13.89%	14.78%	14.78%
Scenario B						
Emission Reduction@ Eth	ton	7236	14,851	14,851	19,181	19,181
Emission Reduction@ Elec	ton	2966,015	2527,201	2527,093	2370,331	2370,331
Total Reduction	ton	2973,251	2542,052	2541,944	2389,512	2389,512
%contribution @Ethanol	% of total	0.24%	0.58%	0.58%	0.80%	0.80%
% contribution @SWP	% of total	56.15%	48.25%	48.25%	44.77%	44.77%
% contribution @SWPvine	% of total	31.72%	37.27%	37.27%	39.64%	39.64%
% contribution @Ricestraw	% of total	11.88%	13.90%	13.90%	14.79%	14.79%

straw is almost available at any time and in any place, regardless of the existence of bioenergy promotion policies, while sweet potato vine can be available only when such policies are launched.

Fig. 1 shows the major source of crop residuals and biochar application under climate-induced change in crop yields. Because energy crop is planned to plant on idle land, a small change in crop yield will not alter the supply of sweet potato and its vines considerably. The result is presented in Table 5, indicating that the set-aside land engaged in energy crop plantation will be relatively stable, even in the face of climate impacts.

However, change in crop yield does have impacts on rice paddy production and agricultural activities. Fig. (1a) shows that approximately 78.16–99.84% of rice straw comes from the central and northern part of Taiwan, implying that when change in crop yield is likely to occur, production of rice paddy could change a lot. This is explained by that the climate-induced yield change results in a variation of marginal land fertility, causing the farmers to balance their expected revenue by altering planting decisions.

However, the land fertility can be improved with biochar application. This study assumes that the biochar is applied on the cropland to recover the decrease in yield change due to climate impacts. In Fig. (1b) we find that the charred land fluctuates a lot, implying the biochar production alters significantly. This is because that biochar is produced from pyrolysis, types of pyrolysis selected and changes in energy and GHG prices will change the amount of biochar considerably. Therefore, when electricity price increases, fast pyrolysis dominates and the amount of biochar production declines.

Development of bioenergy is costly because it usually involves various support policies and subsidies. As shown in Table 6, the results point out that to develop bioenergy, NT$10.75 to NT$13.61 billion dollars and NT$6.22 to NT$ 5.97 billion dollars will be required to maintain the set-aside and promotion program, respectively. Ceteris paribus, a higher GHG price encourages farmers to utilize more aside land, thereby driving the expenses on energy crop subsidy.

One finding meriting more discussion is the relationship between government expenses and land-use change. Although the expense on

Table 4
Emission reduction capacity of rice straw under various conditions.

Prob. of Crop Yield Change		Low	Moderate	High	Low	Moderate	High
Gasoline Price	NT/L	20	20	20	20	20	20
Electricity Price	NT/kW h	3.6	3.6	3.6	1.8	1.8	1.8
GHG Price	NT/ton	5	5	5	50	50	50
Electricity@ricestraw	%	6.15%	6.25%	6.30%	7.26%	7.27%	10.58%
Offset@ricestraw	%	9.73%	9.88%	9.95%	8.84%	8.87%	8.14%
Electricity@vine	%	17.14%	17.24%	17.29%	20.93%	20.96%	30.50%
Offset @vine	%	27.12%	27.22%	27.30%	25.49%	25.56%	23.47%
Gasoline Price	NT/L	30	30	30	30	30	30
Electricity Price	NT/kW h	1.8	1.8	1.8	3.6	3.6	3.6
GHG Price	NT/ton	25	25	25	25	25	25
Electricity@ricestraw	%	7.47%	7.16%	7.52%	6.15%	6.18%	6.23%
Offset@ricestraw	%	9.49%	9.26%	9.54%	9.74%	9.77%	9.84%
Electricity@vine	%	20.78%	19.94%	20.91%	17.07%	17.20%	17.27%
Offset @vine	%	26.39%	25.79%	26.53%	27.03%	27.19%	27.26%
Gasoline Price	NT/L	25	25	25	40	40	40
Electricity Price	NT/kW h	3.6	3.6	3.6	3.6	3.6	3.6
GHG Price	NT/ton	50	50	50	50	50	50
Electricity@ricestraw	%	6.94%	6.94%	7.00%	7.26%	6.94%	6.73%
Offset@ricestraw	%	8.96%	9.00%	9.01%	8.84%	9.00%	9.12%
Electricity@vine	%	20.02%	20.00%	20.18%	20.93%	20.00%	19.39%
Offset @vine	%	25.84%	25.94%	25.96%	25.48%	25.94%	26.30%
Gasoline Price	NT/L	20	20	20	40	40	40
Electricity Price	NT/kW h	3.6	3.6	3.6	1.8	1.8	1.8
GHG Price	NT/ton	25	25	25	5	5	5
Electricity@ricestraw	%	6.15%	6.17%	6.23%	10.47%	9.87%	10.61%
Offset@ricestraw	%	9.74%	9.76%	9.84%	14.62%	14.10%	14.78%
Electricity@vine	%	17.06%	17.20%	17.27%	28.11%	26.57%	28.46%
Offset @vine	%	27.02%	27.18%	27.26%	39.28%	37.94%	39.64%

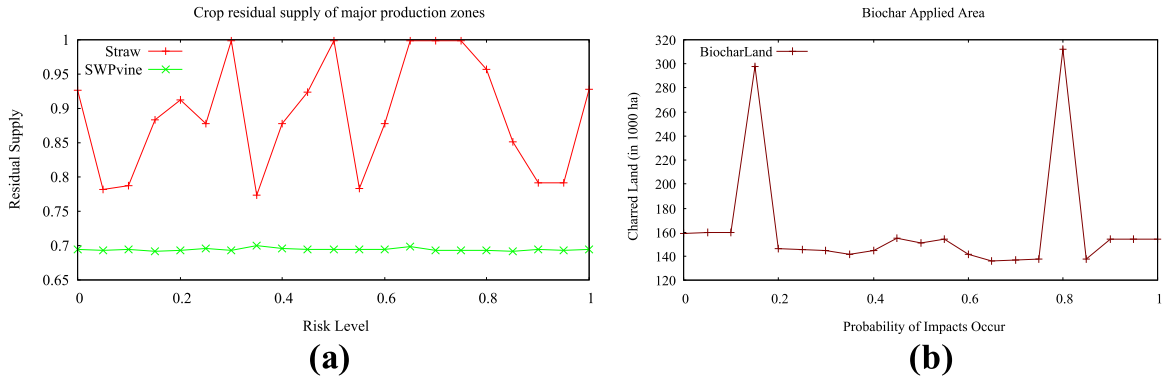

Fig. 1. Residual supply and charred land in major production regions.

Table 5
Percentage of energy crop production from regions.

Risk	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
North	18.16%	18.20%	18.17%	18.28%	18.28%	18.11%	18.24%	17.87%	18.11%	18.16%	18.13%
Central	28.86%	28.91%	28.96%	28.63%	28.67%	29.45%	28.52%	28.98%	29.40%	28.64%	29.06%
South	40.62%	40.50%	40.51%	40.65%	40.60%	40.11%	40.83%	40.99%	40.15%	40.84%	40.47%
East	12.36%	12.39%	12.36%	12.44%	12.44%	12.33%	12.41%	12.16%	12.33%	12.36%	12.34%
Risk	**55%**	**60%**	**65%**	**70%**	**75%**	**80%**	**85%**	**90%**	**95%**	**100%**	
North	18.17%	18.15%	17.93%	18.23%	18.27%	18.22%	18.31%	18.20%	18.20%	18.20%	
Central	28.88%	29.24%	28.00%	29.05%	28.43%	29.10%	28.42%	28.90%	28.90%	28.80%	
South	40.58%	40.26%	41.87%	40.31%	40.87%	40.27%	40.82%	40.52%	40.52%	40.62%	
East	12.37%	12.35%	12.20%	12.41%	12.43%	12.40%	12.46%	12.39%	12.39%	12.39%	

energy crop program is relatively stable, the total aside payment can change considerable in the face of climate impacts. When crop yields decrease, more cropland becomes economic inefficient to engage in production or need to switch its current practice to other types of crops. Under such a circumstance, the portion of land that will eventually be set idle increases, and thus increasing government expenses on aside program.

There is complexity to perfectly distinguish the individual effect of land-use change, government expenditure, types of bioenergy, climate impacts, and emission reduction, all of which requires a modification of modeling structure, but the results indicate that the aggregate effect of bioenergy production in Taiwan can increase social welfare. Fig. 2 depicts the change in social welfare under threats of climate impacts. We show that when a decrease in crop yields is likely to occur, land-use

Table 6
Government expense to support bioenergy development under various climate and market conditions.

Probability of yield change		Low	High	Low	High	Low	High
Gasoline Price	NT/L	20	20	20	20	20	20
Electricity Price	NT/kW h	1.8	1.8	1.8	1.8	3.6	3.6
GHG Price	NT/ton	50	50	5	5	5	5
Scenario A2							
SWP Subsidy	Million NT	6435.89	6435.90	5971.55	5963.11	6222.85	6127.09
SWP Ha	1000 ha	128.72	128.72	119.43	119.26	124.46	122.54
Aside Subsidy	Million NT	11,623.05	13,400.65	13,609.63	13,567.71	10,752.14	13,128.82
Scenario B2							
SWP Subsidy	Million NT	6435.89	6437.39	5971.55	5961.53	6222.85	6127.83
SWP Ha	1000 ha	128.72	128.75	119.43	119.23	124.46	122.56
Aside Subsidy	Million NT	11,623.05	11,880.29	13,609.63	13,601.98	10,752.14	12,908.11
Probability of yield change		Low	High	Low	High	Low	High
Gasoline Price	NT/L	20	20	40	40	40	40
Electricity Price	NT/kW h	3.6	3.6	1.8	1.8	1.8	1.8
GHG Price	NT/ton	50	50	5	5	50	50
Scenario A2							
SWP Subsidy	Million NT	6437.46	6437.34	5998.47	5989.18	6437.31	6435.90
SWP Ha	1000 ha	128.75	128.75	119.97	119.78	128.75	128.72
Aside Subsidy	Million NT	12,269.64	12,221.27	11,945.00	11951.32,	11,903.88	11,852.43
Scenario B2							
SWP Subsidy	Million NT	6437.46	6437.34	5998.47	5987.49	6437.36	6437.40
SWP Ha	1000 ha	128.75	128.75	119.97	119.75	128.75	128.75
Aside Subsidy	Million NT	12,269.64	12,145.66	11,945.00	11,950.68	11,903.88	13,406.44

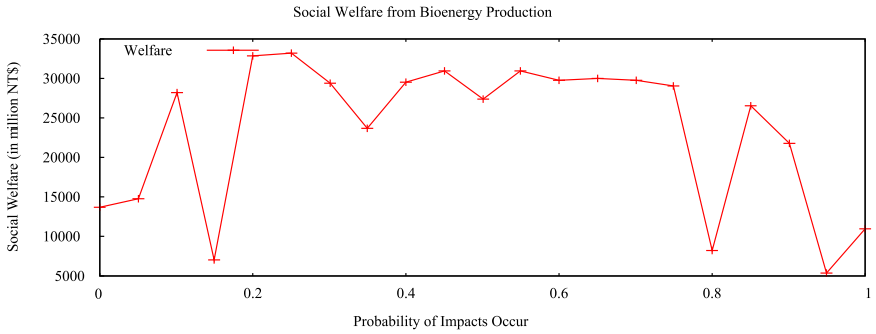

Fig. 2. Welfare change from bioenergy production.

pattern and allocation of resources will shift, and a portion of benefits will be offset by social expenses (i.e., subsidies). This part of result derives a potentially useful policy implication: an appropriate investigation of government subsidy on the programs of energy crop plantation, residual treatments, and set-aside land must be conduct to ensure they can be employed effectively and efficiently. For example, when facing changes (decreases) in crop yield, farmers with least fertile land will choose to set aside their land and labors may flow to other industries, thereby reducing the resources engaged in agricultural sector and hampering the development of bioenergy. To ensure that the bioenergy can be a stable source replacing nuclear power in the near future, such concerns must be thoroughly investigated so that the effectiveness of energy policies is achieved.

5. Conclusions

In 2025, nuclear power that provides 16% of Taiwan's electricity supply will be phased out and replaced by renewable energy. Since bioenergy is an immediate source that is considered to provide stable and sustainable energy to cover this shortage, examination of its effectiveness is an urgent task. This study develops a two-stage stochastic programming with recourse model to analyze how such potential electricity shortage could be recovered by bioenergy under various climate and market conditions. We show that, at best, pyrolysis can recover 2.26% of annual electricity when crop residuals are jointly utilized, implying that a promotion policy of residual treatment is required to encourage collection, transportation, processing, and converting crop and agricultural residuals. In recent years the Taiwanese government has paid extraordinary attention on energy crop plantation, but how to use crop residual efficiently should also be taken into account so that the agricultural resources can be utilized thoroughly and efficiently.

The results indicate that regardless of climate impacts, net electricity and ethanol production are primarily influenced by economic factors such as gasoline, electricity and GHG prices, implying that the climate-induced change in crop yield would not be the primary factor influencing bioenergy production. However, potential changes in land use and resource allocation may be large, which require additional investigation to ensure the sustainable agricultural practice. Since the current electricity price in Taiwan is approximately NT$2.6/kW h and is expected to approach NT$3/kW h in the near future, pyrolysis, especially the fast pyrolysis, might be a good choice to adopt to avoid energy shortage. However, since bioenergy along only recovers one-seventh of electricity supply of nuclear power, other forms of renewable energy such as hydropower, solar energy, and wind power should also be investigated.

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